

CFD Analysis of Spray Combustion and Radiation  
in OMV Thrust Chamber

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ABSTRACT

The Variable Thrust Engine (VTE), developed by TRW, for the Orbit Maneuvering Vehicle (OMV) uses a hypergolic propellant combination of Monomethyl Hydrazine (MMH) and Nitrogen Tetroxide (NTO) as fuel and oxidizer, respectively. The propellants are pressure fed into the combustion chamber through a single pintle injection element. The performance of this engine is dependent on the pintle geometry and a number of complex physical phenomena and their mutual interactions. The most important among these are: (1) atomization of the liquid jets into fine droplets; (2) the motion of these droplets in the gas field; (3) vaporization of the droplets; (4) turbulent mixing of the fuel and oxidizer; and (5) hypergolic reaction between MMH and NTO.

Each of the above phenomena by itself poses a considerable challenge to the technical community. In a reactive flow field of the kind occurring inside the VTE, the mutual interactions between these physical processes tend to further complicate the analysis.

The objective of this work is to develop a comprehensive mathematical modeling methodology to analyze the flow field within the VTE. Using this model, the effect of flow parameters on various physical processes such as atomization, spray dynamics, combustion, and radiation is studied. This information can then be used to optimize design parameters and thus improve the performance of the engine.

The REFLEQS CFD Code is used for solving the fluid dynamic equations. The spray dynamics is modeled using the Eulerian-Lagrangian approach. The discrete ordinate method with 12 ordinate directions is used to predict the radiative heat transfer in the OMV combustion chamber, nozzle, and the heat shield. The hypergolic reaction between MMH and NTO is predicted using an equilibrium chemistry model with 13 species.

The results indicate that mixing and combustion is very sensitive to the droplet size. Smaller droplets evaporate faster than bigger droplets, leading to a well mixed zone in the combustion chamber. The radiative heat flux at combustion chamber and nozzle walls are an order of magnitude less than the conductive heat flux. Simulations performed with the heat shield show that a negligible amount of fluid is entrained into the heat shield region. However, the heat shield is shown to be effective in protecting the OMV structure surrounding the engine from the radiated heat.

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**11th CFD Workshop**  
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# **OUTLINE**



- **Introduction**
- **Physical Models**
  - **Atomization Model**
  - **Spray Model**
  - **Combustion Model**
  - **Radiation Model**
- **REFLEQS Flow Solver**
- **Computational Results**
- **Conclusions**

# **INTRODUCTION**

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## **Variable Thrust Engine (VTE) for Orbital Maneuvering Vehicle (OMV)**

- **Planned for Operations in Outer Space**
- **Relatively Low Power Engine**
- **Continuous Thrust Variation from 0 to 100%**
- **Hypergolic Liquid Reactants:**
  - **Fuel - Monomethyl Hydrazine (MMH)**
  - **Oxidizer - Nitrogen Tetroxide (NTO)**
- **Pintle Injector**

# **INTRODUCTION**



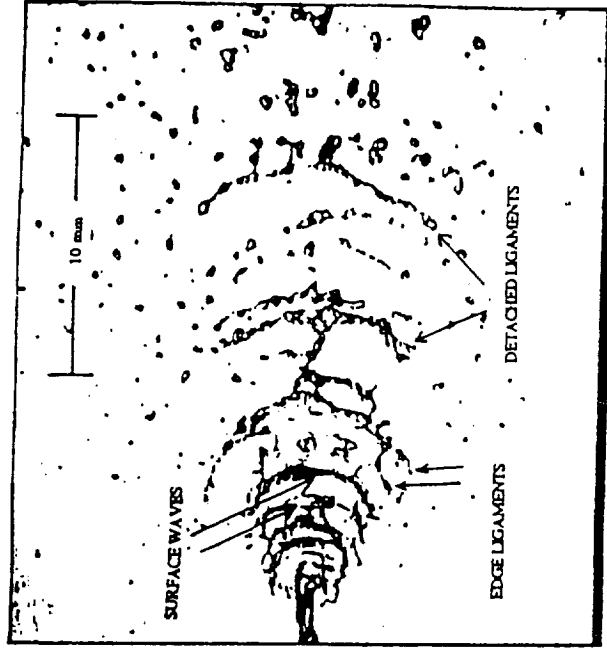
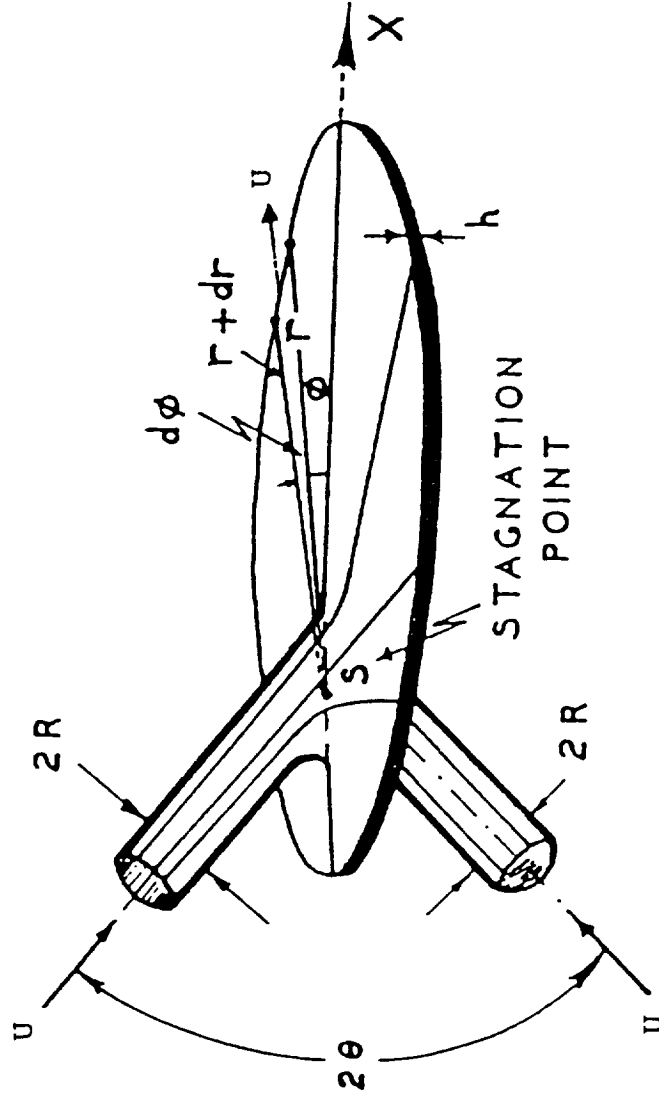
## **Important Issues**

- **Modeling Atomization is Crucial for Predicting Initial Drop Sizes**
- **Vaporization, Mixing and Combustion**
- **Effects of Radiation and Quantify Radiative Heat Loss**

# PHYSICAL MODELS

## Impinging Jets Atomization

CFDRC



Anderson et al. (1992)

## **Spray Model**

- Eulerian-Lagrangian Approach
- Improved Version of PSI-CELL Method
- Deterministic Droplet Tracking
- Droplet Turbulent Dispersion Model based on Gosmann and Ioannides (1981)
- Droplet Size Distributions
- Coupled Droplet Source/Sink Terms for the Gas Phase

## **Combustion Models**

- Reaction between MMH & NTO is Hypergolic
- Instantaneous Chemistry
- Finite-Rate Chemistry
- Equilibrium Chemistry
  - based on the element potential method
  - minimization of Gibbs function of the system
  - 13 species ( $\text{CH}_6\text{N}_2$ ,  $\text{N}_2\text{O}_4$ ,  $\text{H}$ ,  $\text{H}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{NO}$ ,  $\text{CO}$ ,  $\text{CH}_4$ ,  $\text{N}_2$ ,  $\text{O}$ ,  $\text{OH}$ ,  $\text{O}_2$ ,  $\text{CO}_2$ )



## **Radiation Model**

- **Several Methods are Available**
  - **Flux Methods**
  - **Discrete Transfer Method**
  - **P-N Approximation**
  - **Monte-Carlo Method**
  - **Holtel's Zone Method**
  - **Discrete-Ordinate Method**
- **For Complex BFC Geometries such as OMV**
- **Study Effects of Radiation on the Flow**
- **Estimate Radiative Heat Flux**

## Discrete-Ordinate Radiation Model

### Radiative Transfer Equation

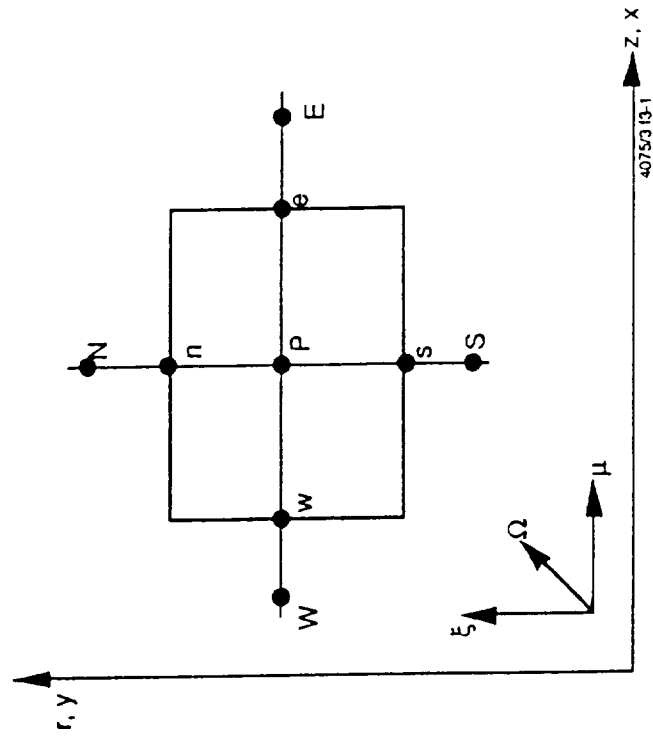
$$(\Omega \cdot \nabla) I = -(k + \sigma) I + k I_b + \frac{\sigma}{4\pi} \int_{\Omega=4\pi} I \phi(\Omega' \rightarrow \Omega) d\Omega'$$

$I(r, \Omega)$  = Radiation Intensity

$k$  = adsorption coefficient

$\sigma$  = scattering coefficient

$I_b$  = Black Body Intensity



- **Solves Favre-Average Navier-Stokes Equations Using the Finite-Volume Approach**
- **Fully Implicit and Conservative Pressure-Based Solution Algorithm**
- **Cartesian and BFC Formulation**
- **k- $\epsilon$  Turbulence Model**
- **Source/Sink Terms Due to Spray, Combustion, and Radiation**

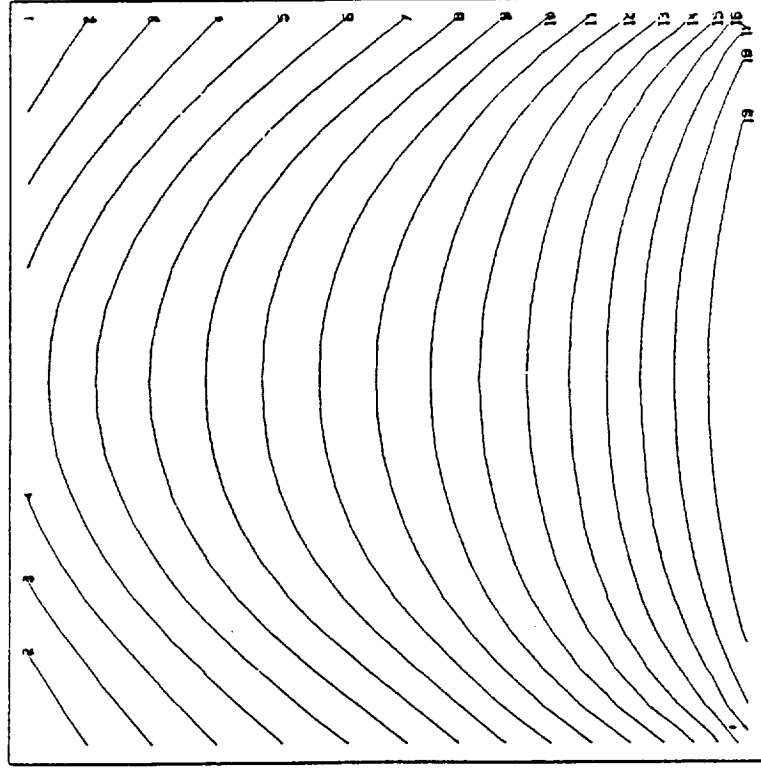
# RESULTS



## Radiation Model Validation

### Temperature Distribution in a Square Enclosure (Bottom Wall - 1000°K, Other Walls - 0°K)

TEMP CONTOURS  
FMIN 5 063E+02  
FMAX 8 796E+02  
CONTOUR LEVELS  
1 5 063E+02  
2 5 260E+02  
3 5 456E+02  
4 5 653E+02  
5 5 849E+02  
6 6 046E+02  
7 6 242E+02  
8 6 439E+02  
9 6 635E+02  
10 6 831E+02  
11 7 028E+02  
12 7 224E+02  
13 7 421E+02  
14 7 617E+02  
15 7 814E+02  
16 8 010E+02  
17 8 207E+02  
18 8 403E+02  
19 8 599E+02  
20 8 796E+02  
OK >



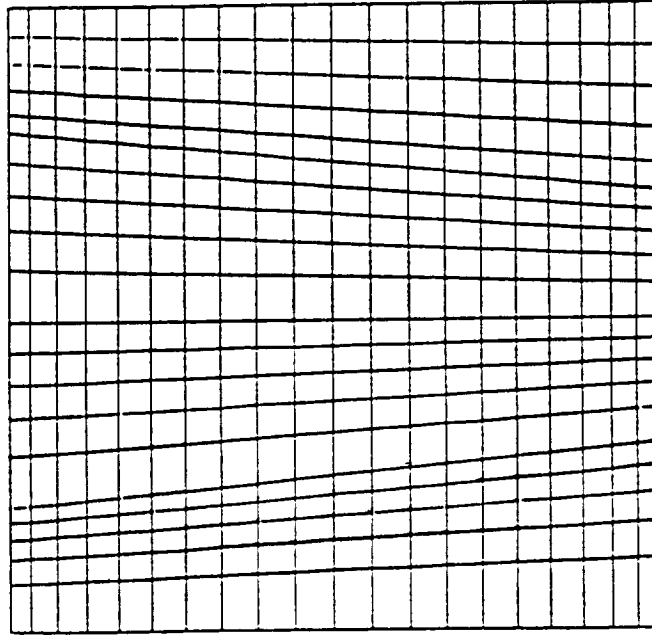
Grid Size 20 x 20

# RESULTS

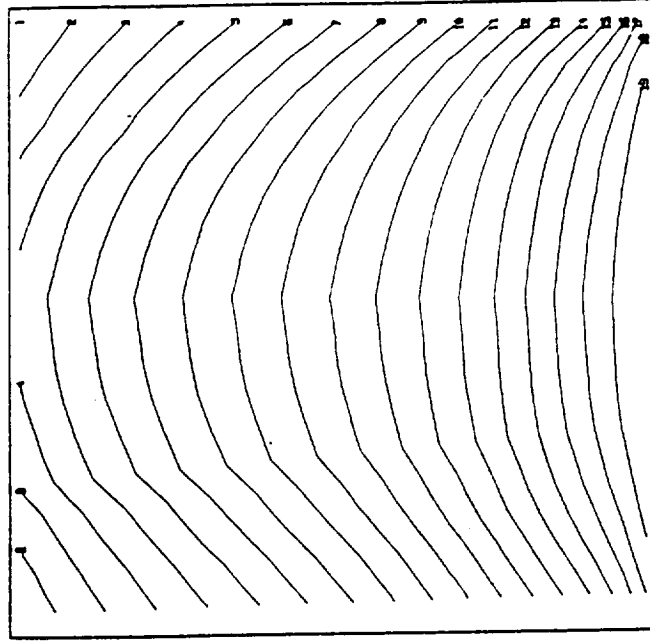
## Radiation Model Validation



### Temperature Distribution in a Square Enclosure with Non-Orthogonal Grid



XY PLANE 1  
TEMP CONTOURS  
FMIN 5.063E+02  
FMAX 8.832E+02  
CONTOUR LEVELS  
1 5.063E+02  
2 5.262E+02  
3 5.460E+02  
4 5.658E+02  
5 5.857E+02  
6 6.055E+02  
7 6.253E+02  
8 6.452E+02  
9 6.650E+02  
10 6.848E+02  
11 7.047E+02  
12 7.245E+02  
13 7.443E+02  
14 7.642E+02  
15 7.840E+02  
16 8.038E+02  
17 8.237E+02  
18 8.435E+02  
19 8.633E+02  
20 8.832E+02  
OK>



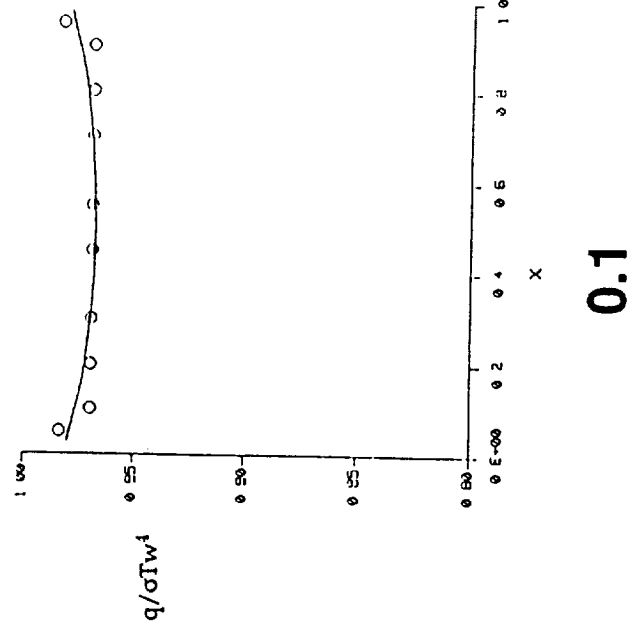
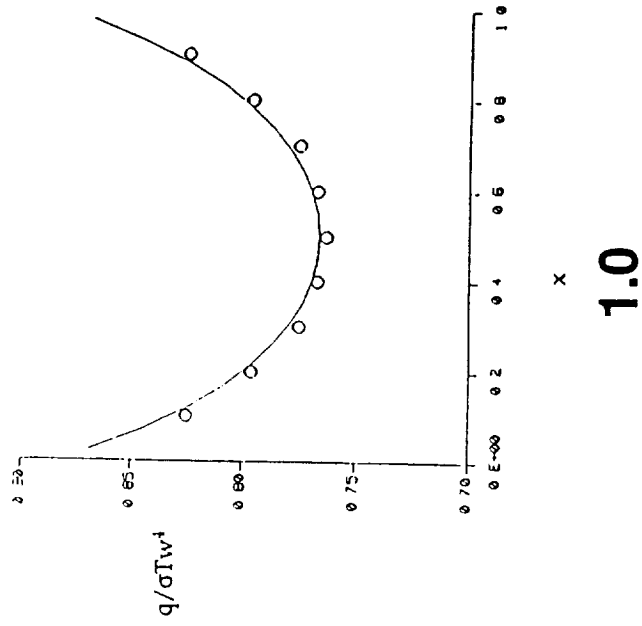
Grid Size 20 x 20

# RESULTS

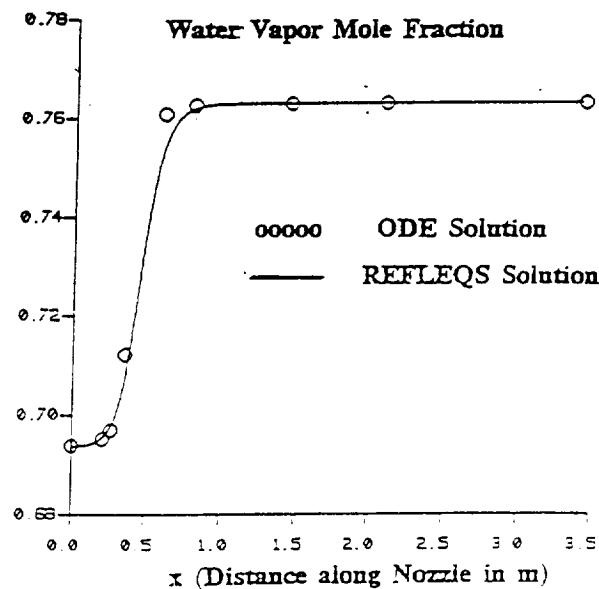
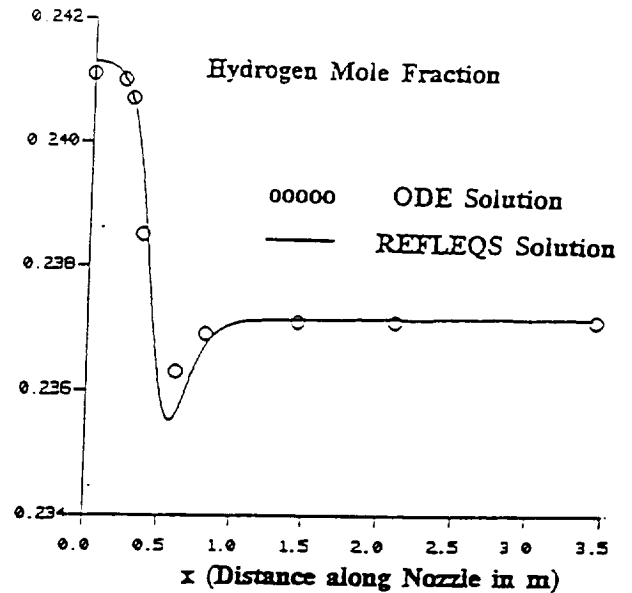
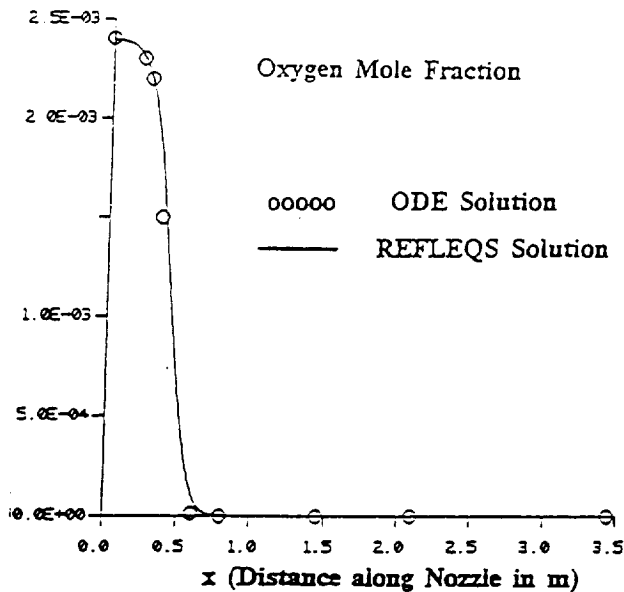
## Radiation Model Validation



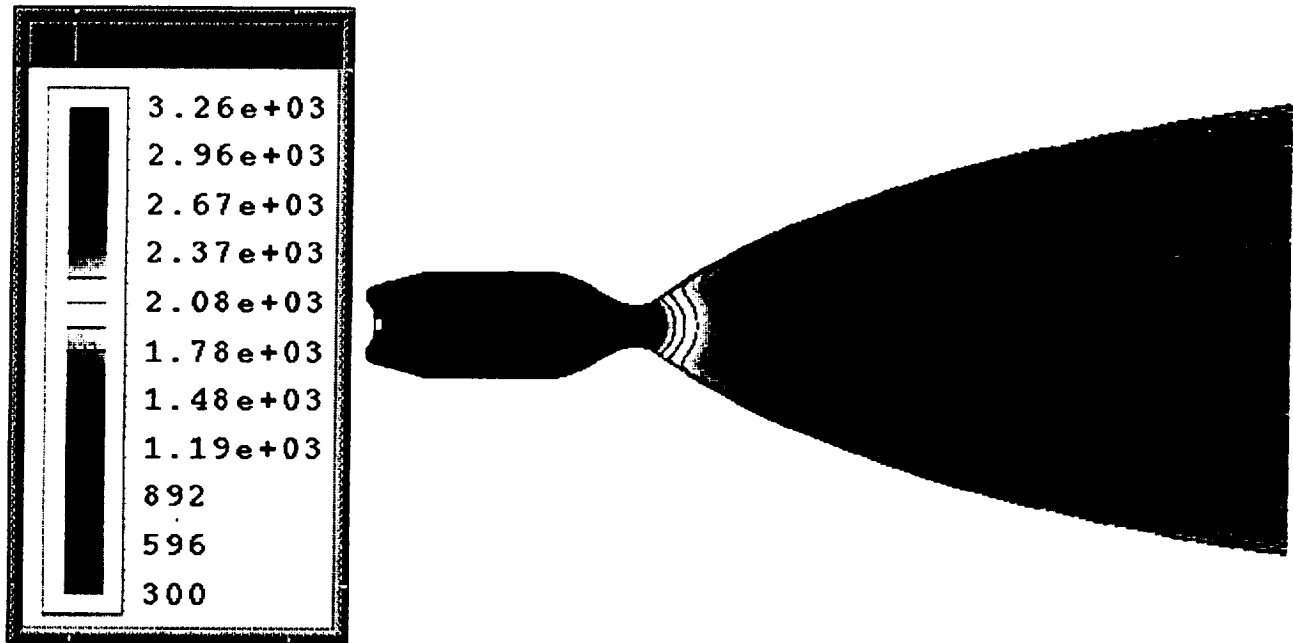
### Radiative Heat Transfer at the Hot Wall of a Square Enclosure for Various Absorption Cross-Sections



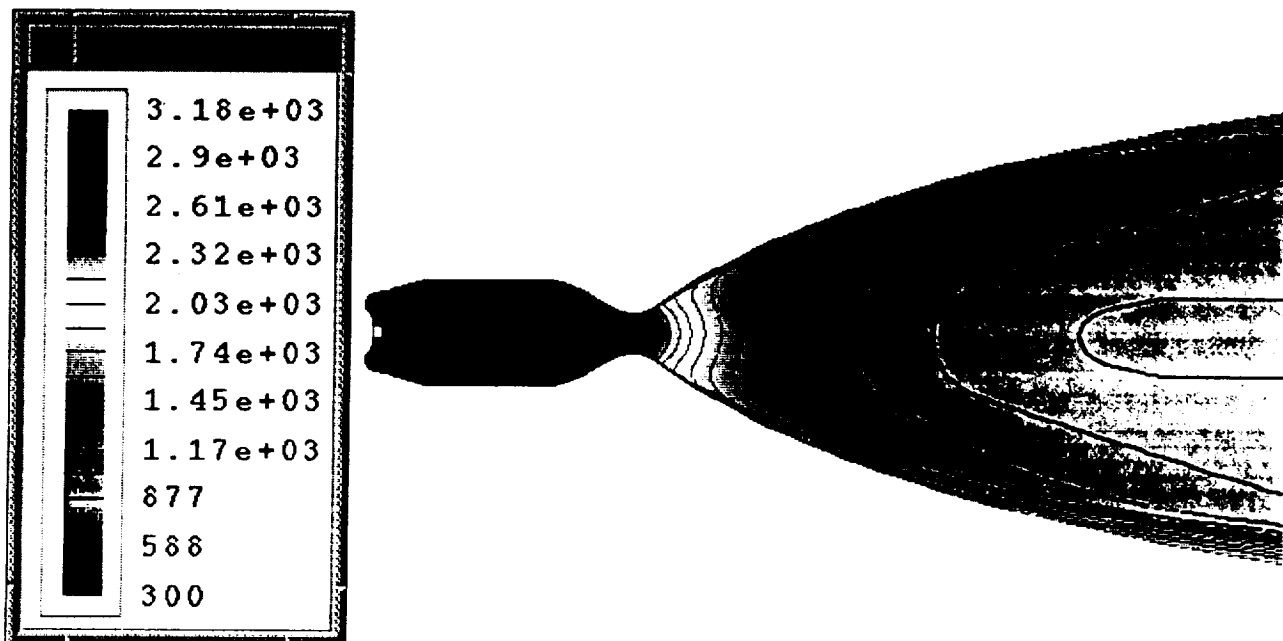
## Equilibrium Chemistry Model Validation



TEMPERATURE DISTRIBUTION IN VTE CHAMBER/NOZZLE  
(GAS-GAS MODEL)



100% POWER LEVEL



50% POWER LEVEL

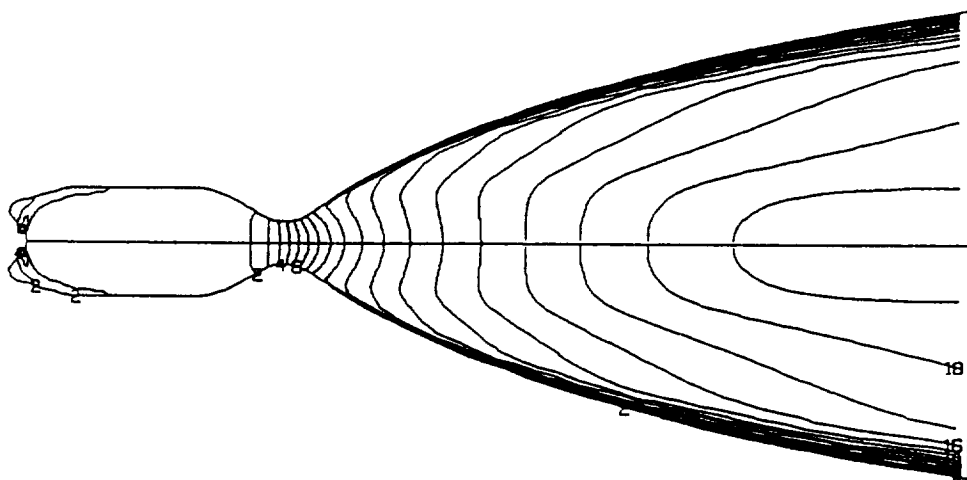


# RESULTS



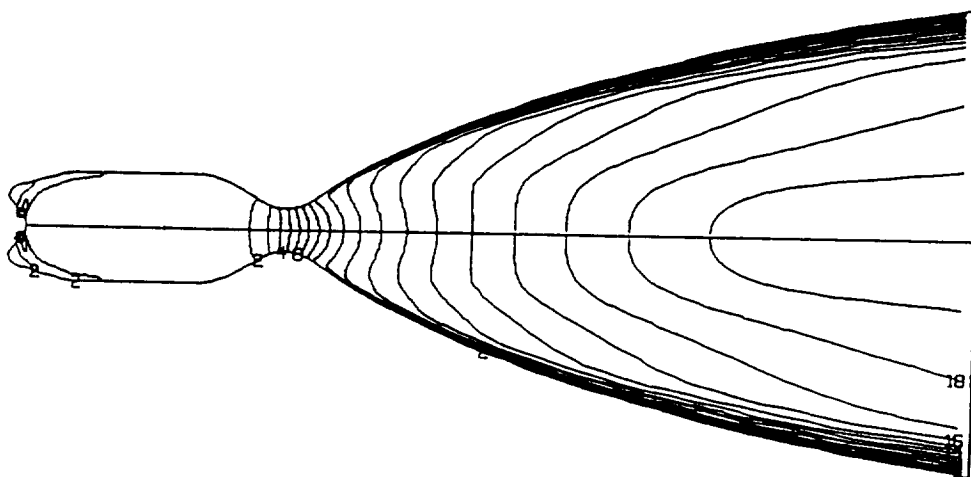
## Mach Number Distribution in VTE Chamber/Nozzle (Gas-Gas Model)

MACH CONTOURS  
FMIN 2.162E-03  
FMAX 5.049E+00  
CONTOUR LEVELS  
2 2.678E-01  
4 7.990E-01  
6 1.330E+00  
8 1.862E+00  
10 2.393E+00  
12 2.924E+00  
14 3.455E+00  
16 3.987E+00  
18 4.518E+00  
20 5.049E+00



### 100% Power Level

MACH CONTOURS  
FMIN 2.442E-03  
FMAX 4.921E+00  
CONTOUR LEVELS  
2 2.613E-01  
4 7.790E-01  
6 1.297E+00  
8 1.814E+00  
10 2.332E+00  
12 2.850E+00  
14 3.368E+00  
16 3.885E+00  
18 4.403E+00  
20 4.921E+00



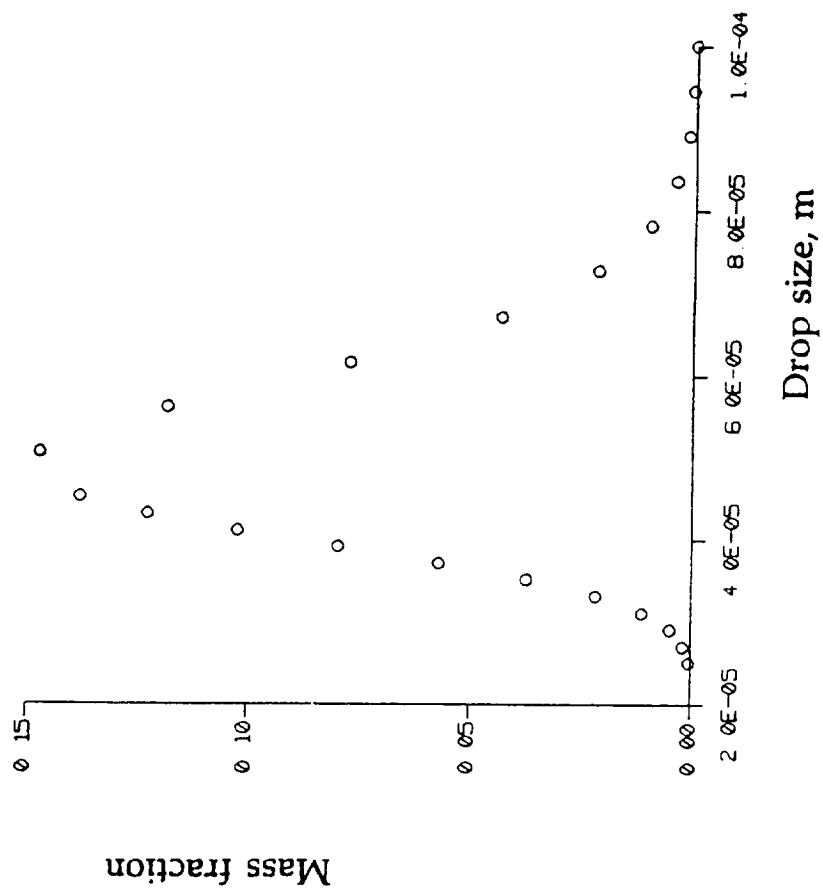
### 50% Power Level

# RESULTS

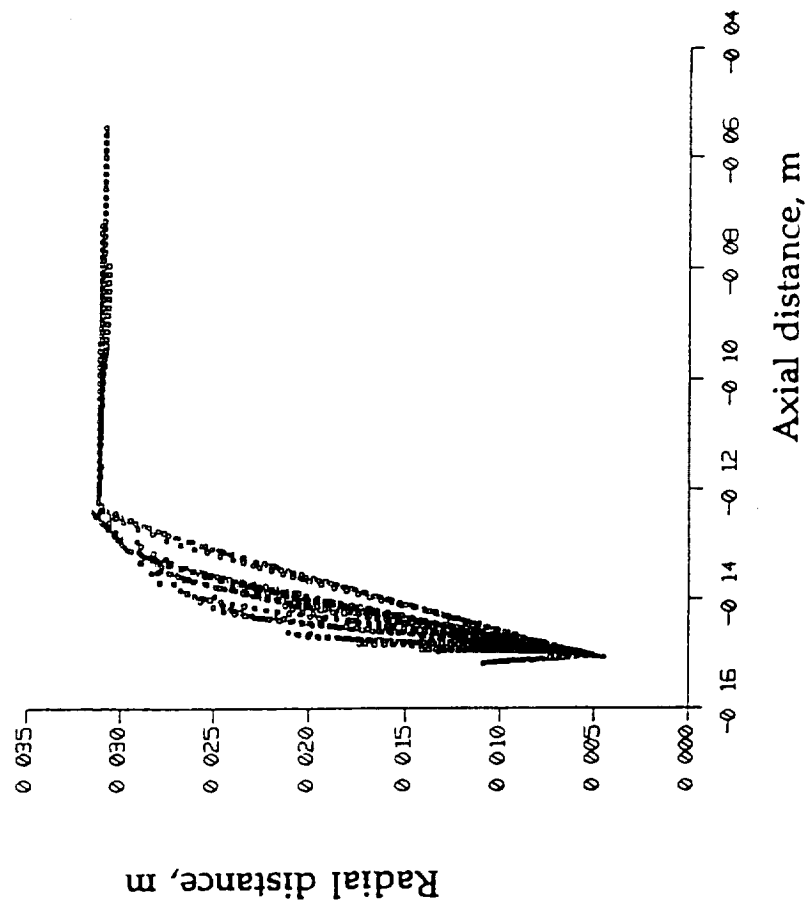
## Spray Model

CFDRC

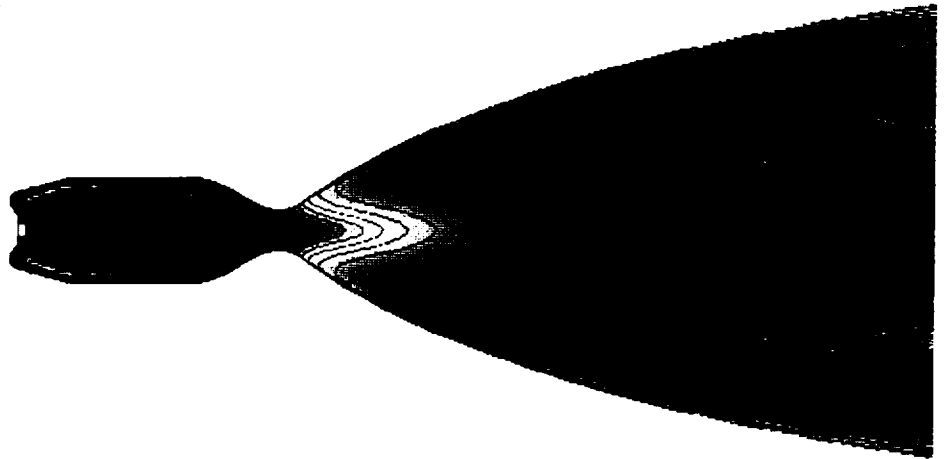
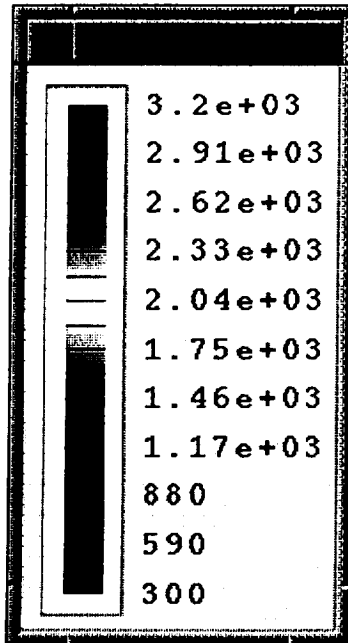
### Drop Size Distribution



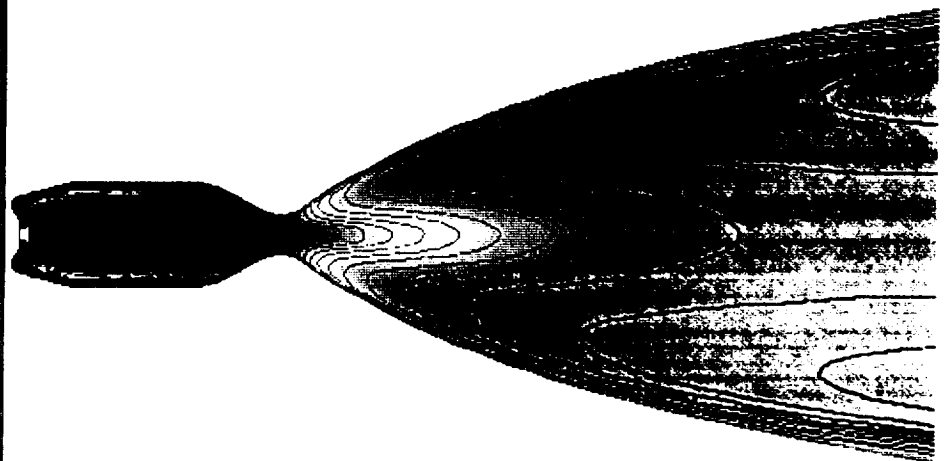
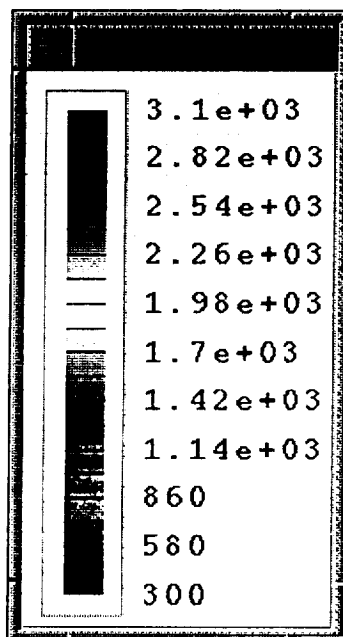
### Droplet Trajectories



**TEMPERATURE DISTRIBUTION IN VTE CHAMBER/NOZZLE  
(SPRAY MODEL)**



**100% POWER LEVEL**



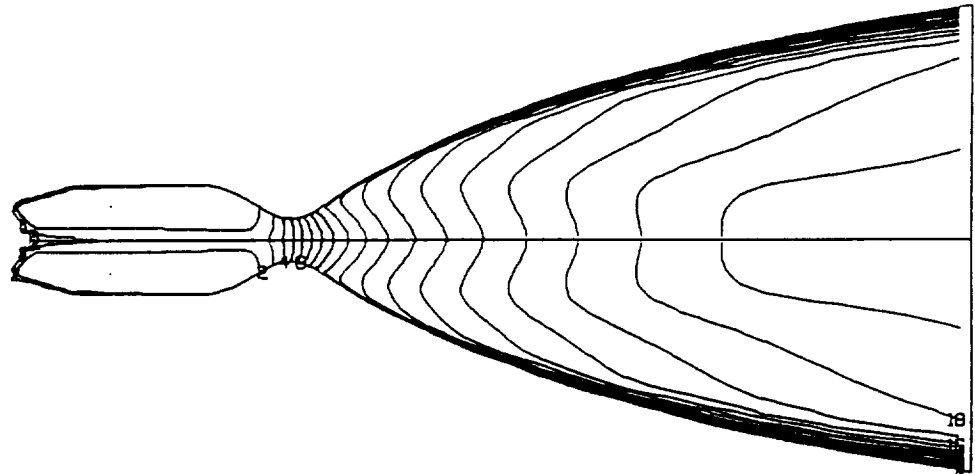
**50% POWER LEVEL**

# RESULTS

# CFDRC

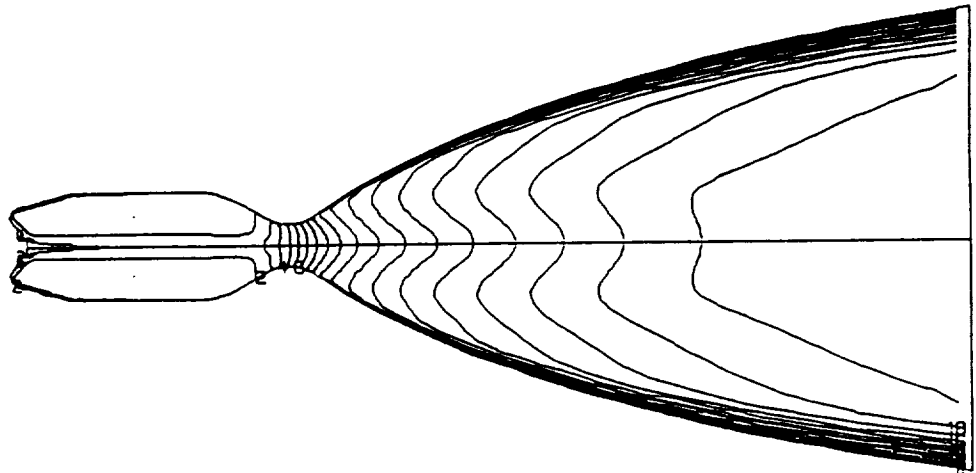
## Mach Number Distribution in VTE Chamber/Nozzle (Spray Model)

MACH CONTOURS  
FMIN 3.139E-04  
FMAX 4.786E+00  
CONTOUR LEVELS  
2 2.522E-01  
4 7.559E-01  
6 1.260E+00  
8 1.763E+00  
10 2.267E+00  
12 2.771E+00  
14 3.275E+00  
16 3.778E+00  
18 4.282E+00  
20 4.786E+00



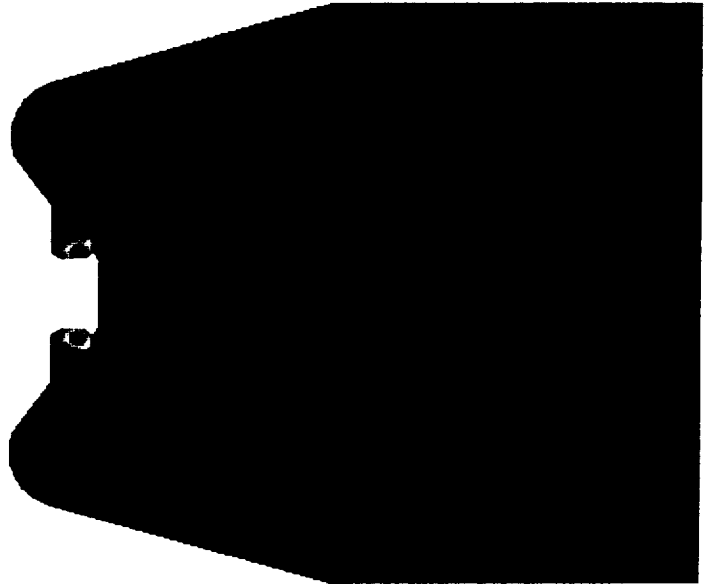
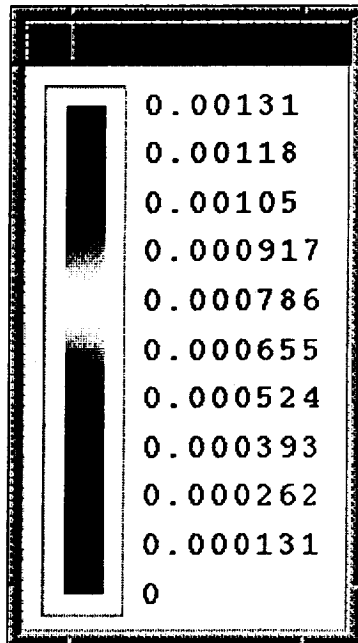
### 100% Power Level

MACH CONTOURS  
FMIN 4.754E-04  
FMAX 4.556E+00  
CONTOUR LEVELS  
2 2.402E-01  
4 7.198E-01  
6 1.199E+00  
8 1.679E+00  
10 2.158E+00  
12 2.638E+00  
14 3.117E+00  
16 3.597E+00  
18 4.077E+00  
20 4.556E+00

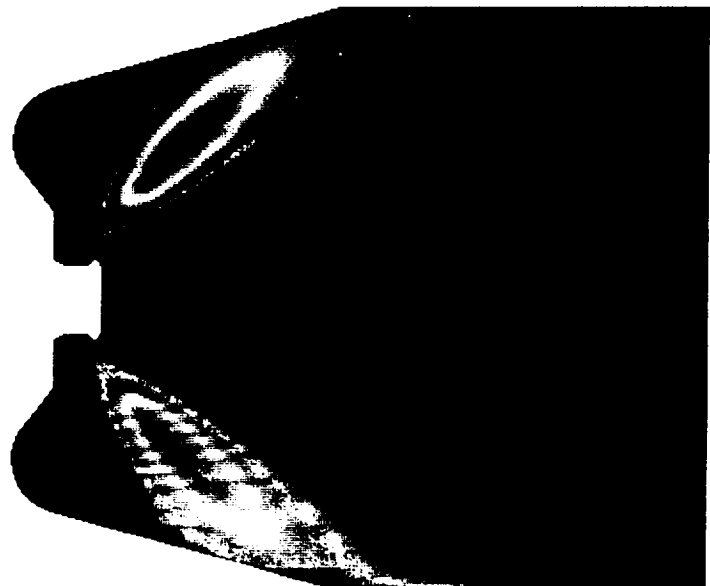
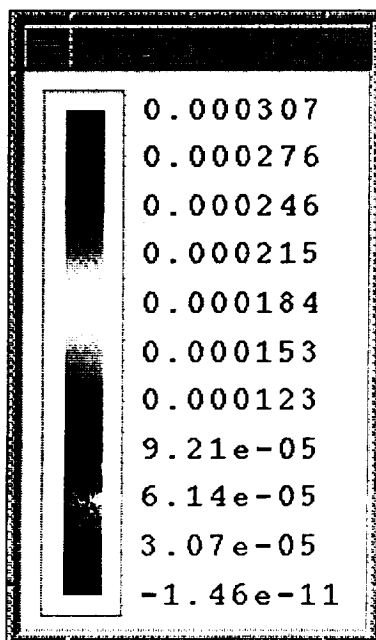


### 50% Power Level

# EVAPORATED NTO MASS DISTRIBUTION IN VTE CHAMBER (100% POWER LEVEL)

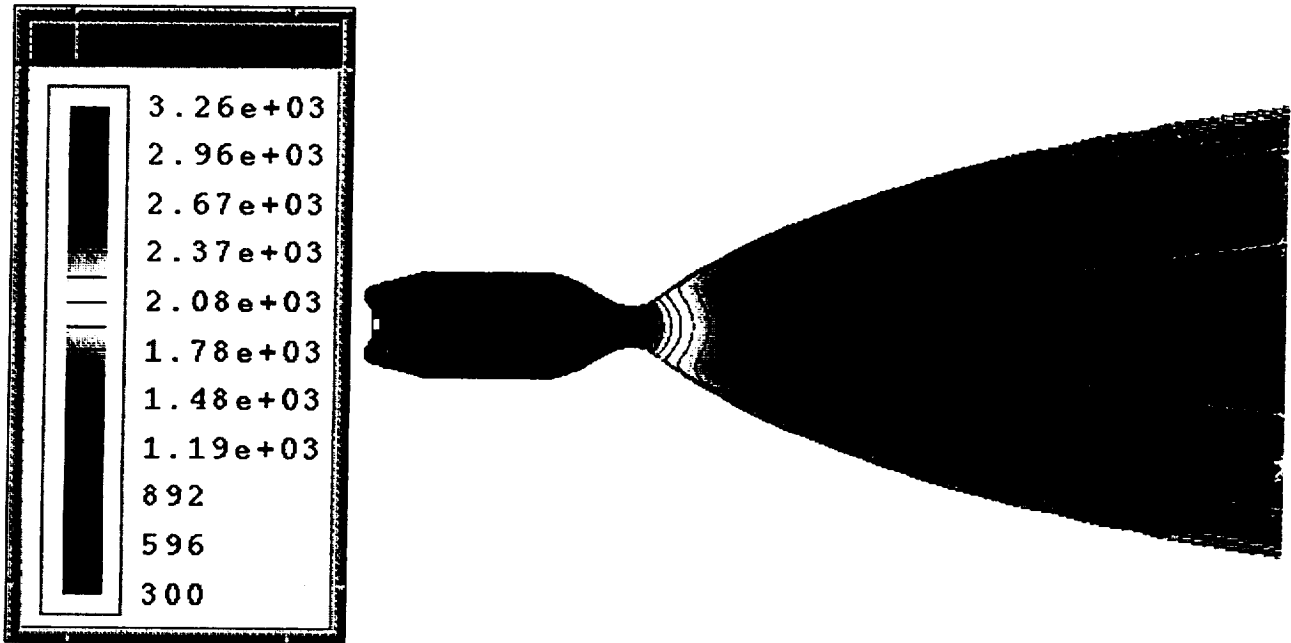


25 MICRON MEAN DROP SIZE

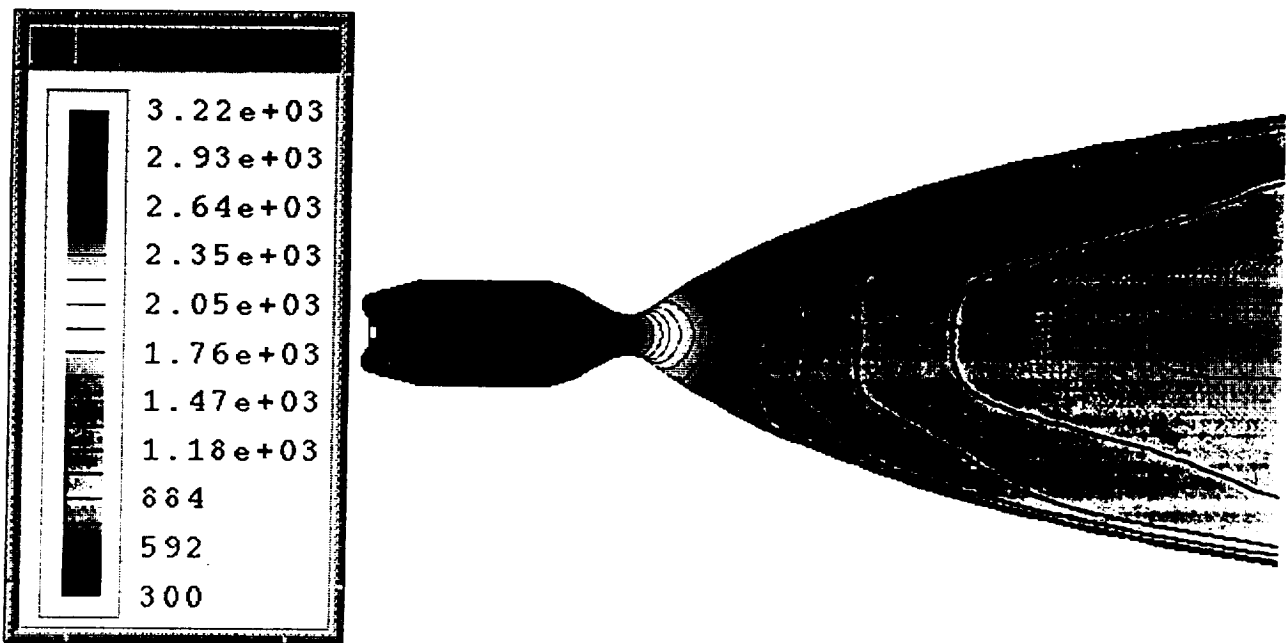


100 MICRON MEAN DROP SIZE

# EFFECT OF RADIATION IN VTE CHAMBER/NOZZLE (TEMPERATURE DISTRIBUTION, 100% POWER LEVEL)



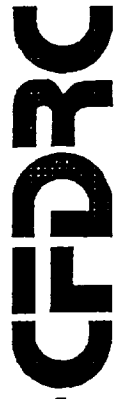
NO RADIATION



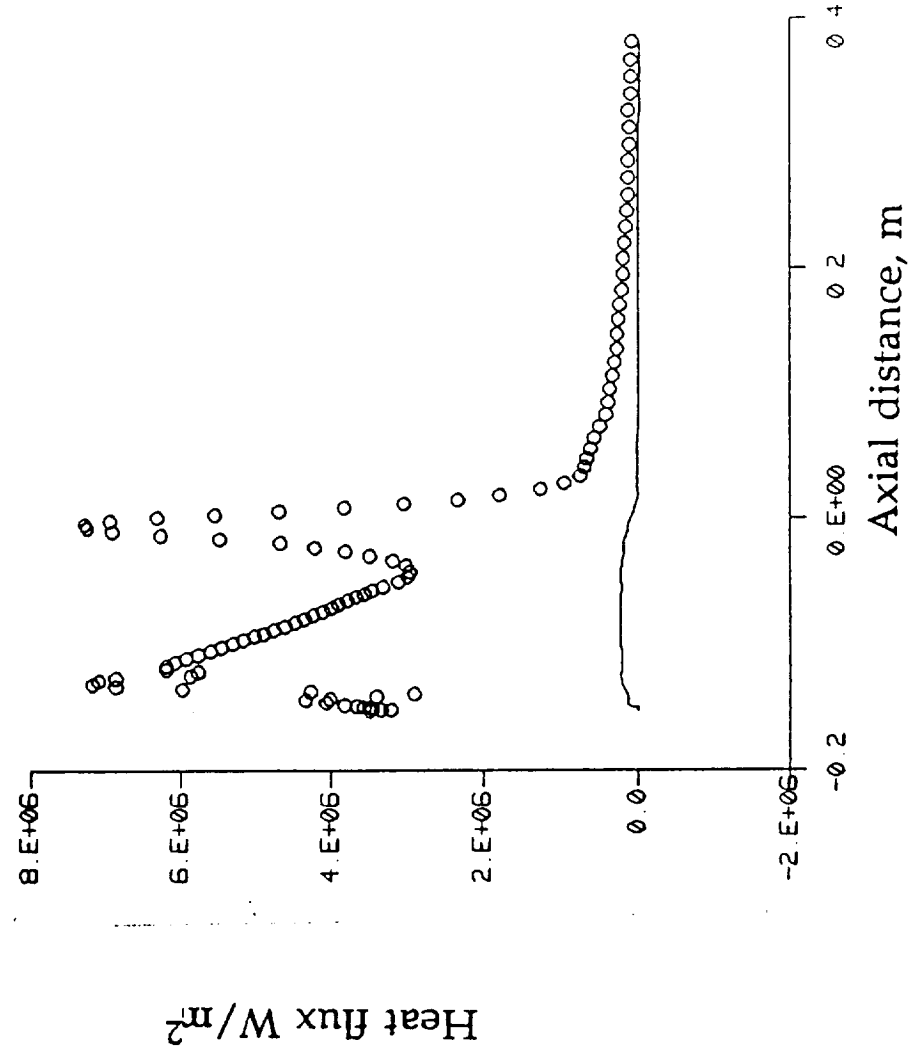
WITH RADIATION

# RESULTS

## Radiation Model



### Comparison of Conductive and Radiative Heat Fluxes

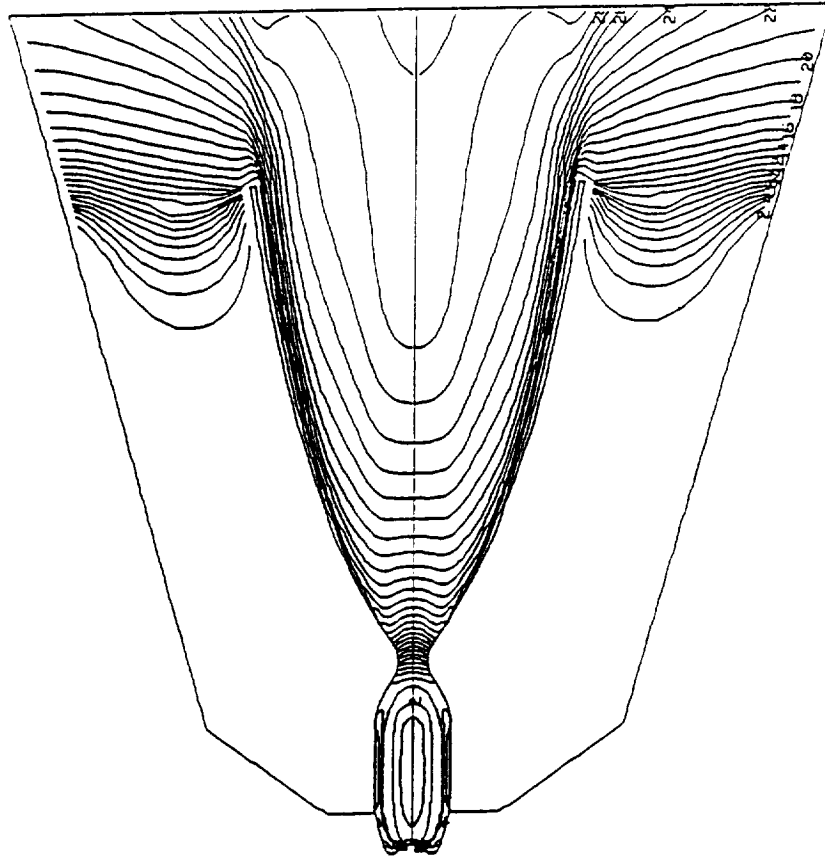


# RESULTS



## Mach Number Distribution in VTE Chamber/Nozzle/Heat Shield

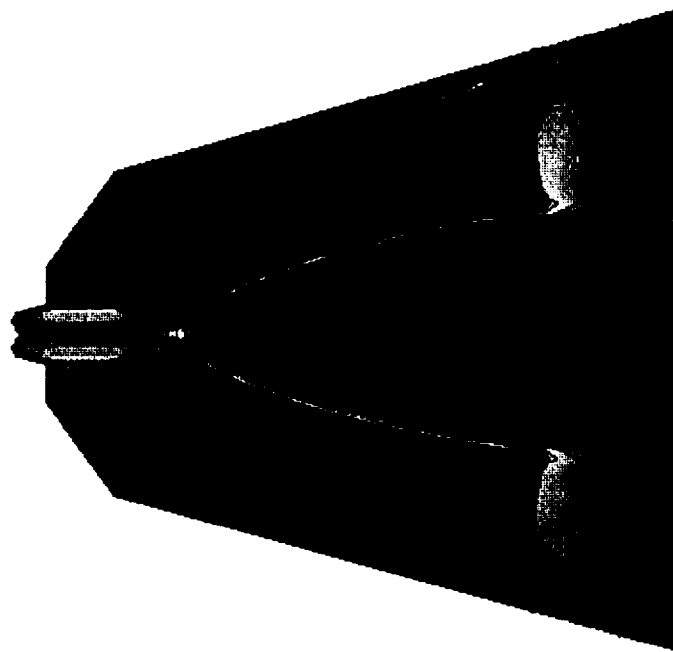
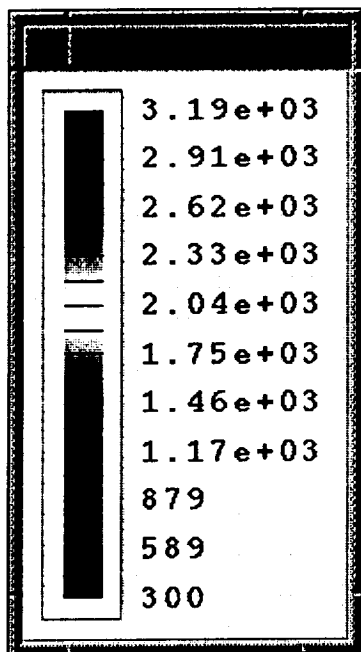
MACH CONTOURS  
FMIN 2.140E-08  
FMAX 4.817E+00  
CONTOUR LEVELS  
2 1.661E-01  
4 4.983E-01  
6 8.305E-01  
8 1.163E+00  
10 1.495E+00  
12 1.827E+00  
14 2.159E+00  
16 2.492E+00  
18 2.824E+00  
20 3.156E+00  
22 3.488E+00  
24 3.821E+00  
26 4.153E+00  
28 4.485E+00  
30 4.817E+00



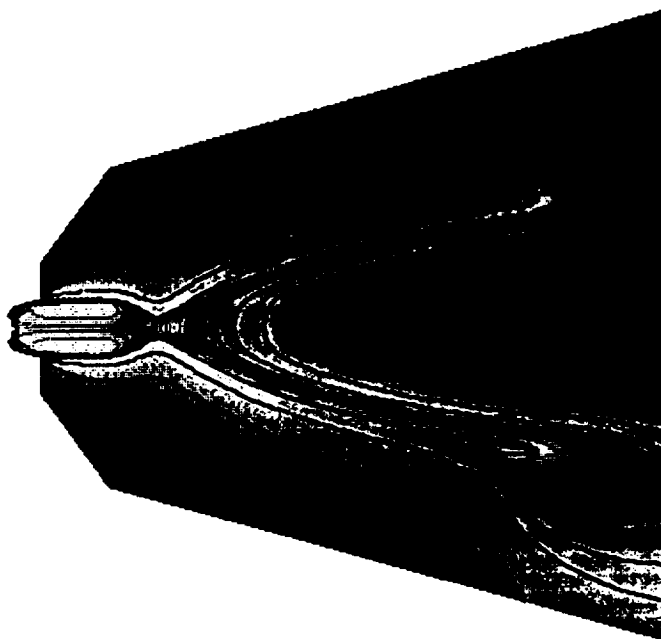
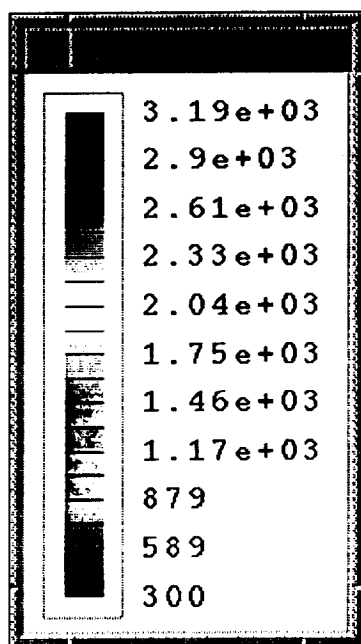
(Gas-Gas Model, 100% Power Level)



# **EFFECT OF RADIATION IN VTE CHAMBER/NOZZLE/HEAT SHIELD (TEMPERATURE DISTRIBUTION, 100% POWER LEVEL)**

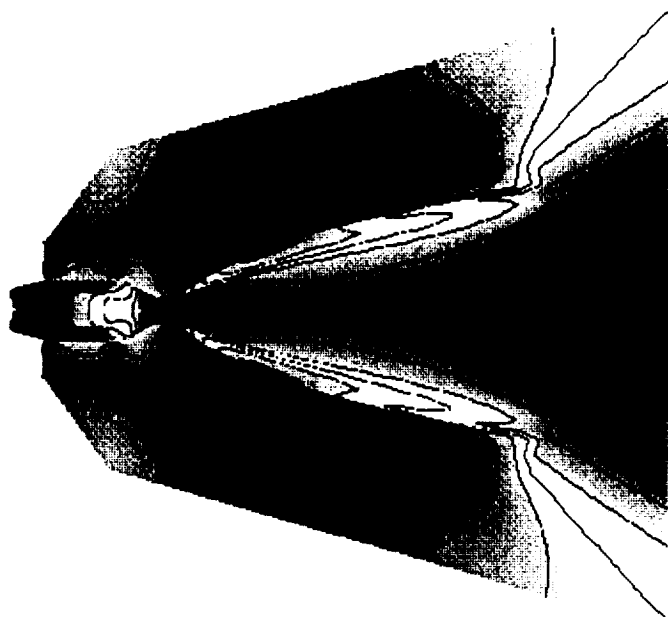
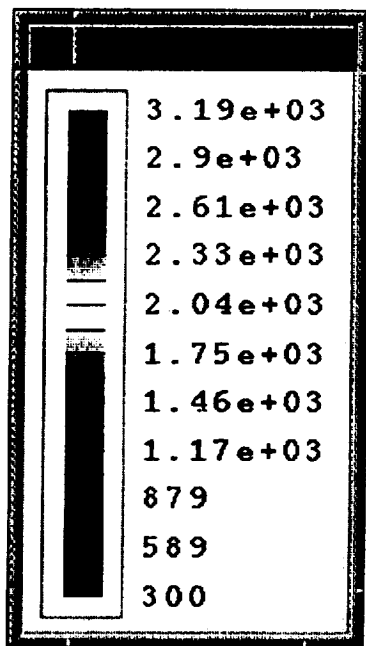


**NO RADIATION**

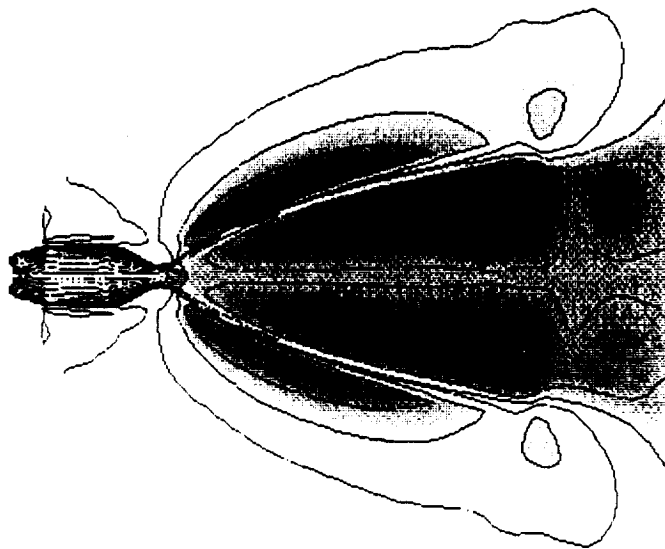
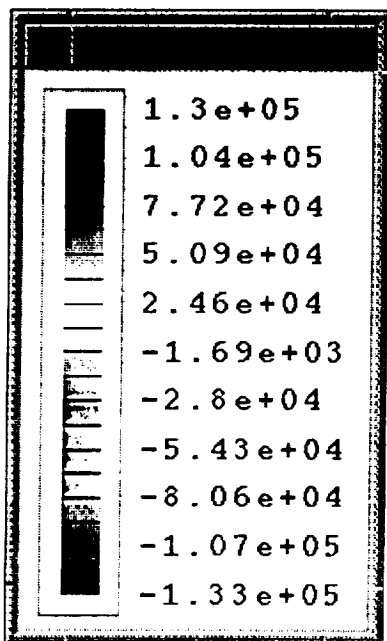


**WITH RADIATION**

# **RADIATIVE FLUX DISTRIBUTION IN VTE CHAMBER/NOZZLE** **(100% POWER LEVEL)**



**AXIAL RADIATIVE FLUX**



**RADIAL RADIATIVE FLUX**

## **CONCLUSIONS**



- Evaluated the Performance of OMV/VTE at Various Power Levels
- BFC Radiation Model Based on the Discrete-Ordinate Method has been Implemented in the REFLEQS Code
- Simulations of Gas-Gas and Liquid Spray Models were Compared
- Smaller Droplets Evaporate Faster Leading to Better Mixing
- Radiative Effects on Flow and Heat Transfer are Insignificant
- Need an Advanced Model for Atomization Due to Impingement of Unlike Liquids

